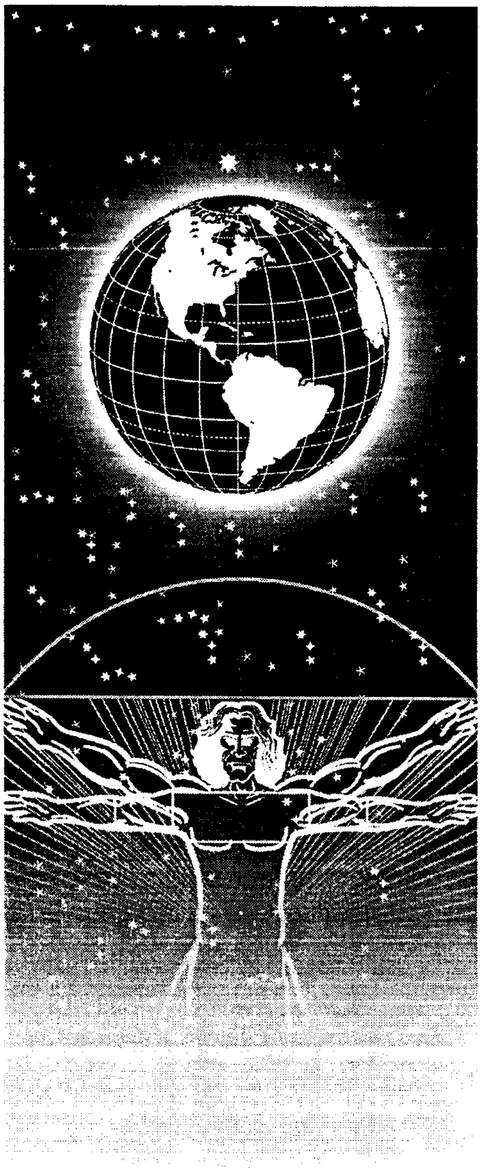
AL/HR-TR-1997-0035



ARMSTRONG LABORATORY

ELIMINATING POSITIONAL DISCREPANCIES ENCOUNTERED DURING INTEGRATION OF DISSIMILAR SYSTEMS ON A DISTRIBUTED INTERACTIVE SIMULATION NETWORK

David J. Lerman
Hughes Training, Inc., Training Operations
6001 South Power Road, Building 560
Mesa AZ 85206-0904

Richard L. Rogers, Major, USAF

Clarence W. Stephens, Jr.

ARMSTRONG LABORATORY
HUMAN RESOURCES DIRECTORATE
AIRCREW TRAINING RESEARCH DIVISION
6001 South Power Road, Building 561
Mesa AZ 85206-0904

July 1997

AIR FORCE MATERIEL COMMAND
ARMSTRONG LABORATORY
HUMAN RESOURCES DIRECTORATE
7909 Lindbergh Drive
Brooks Air Force Base, TX 78235-5352

NOTICES

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely Government-related procurement, the United States Government incurs no responsibility or any obligation whatsoever. The fact that the Government may have formulated or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication, or otherwise in any manner construed, as licensing the holder, or any other person or corporation; or as conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

The Office of Public Affairs has reviewed this report, and it is releasable to the National Technical Information Service, where it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for publication.

CLARENCE W. STEPHENS, JR.
Project Scientist

DEE H. ANDREWS
Technical Director

LYNN A. CARROLL, Colonel, USAF
Chief, Aircrew Training Research Division

Please notify AL/HRPP, 7909 Lindbergh Drive, Brooks AFB, TX 78235-5352, if your address changes, or if you no longer want to receive our technical reports. You may write or call the STINFO Office at DSN 240-3877 or commercial (210) 536-3877.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	July 1997	Final - June 1994 to May 1995

4. TITLE AND SUBTITLE

Eliminating Positional Discrepancies Encountered during Integration of Dissimilar Systems on a Distributed Interactive Simulation Network

5. FUNDING NUMBERS

C - F41624-95-C-5011
PE - 63227F
PR - 2743
TA - 25
WU - 38

6. AUTHOR(S)
David J. Lerman
Richard L. Rogers
Clarence W. Stephens, Jr.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Hughes Training, Inc.
Training Operations
6001 South Power Road, Building 561
Mesa, AZ 85206-0904

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Armstrong Laboratory
Human Resources Directorate
Aircrew Training Research Division
6001 South Power Road, Building 558
Mesa, AZ 85206-0904

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

AL/HR-TR-1997-0035

11. SUPPLEMENTARY NOTES

Armstrong Laboratory Technical Monitor: Mr Clarence W. Stephens, Jr. (602) 988-6561

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
This report is an expanded version of a paper presented at the International Training Equipment Conference (ITEC) '96 held at The Hague, in The Netherlands in April 1996. The principal difference in this report is the inclusion of a description of the simulator network (SIMNET) from which the Distributed Interactive Simulation (DIS) network was developed, and the inclusion of a section on acceleration transformation presented orally at the conference but is not in the written paper. The simulation community faces the challenge of using the DIS protocol to network long established simulation systems that have been developed independently of each other and of DIS. Such simulators might have earth-shape representations that differ from each other and from the DIS protocol standard of the World Geodetic System 1984 (WGS-84) ellipse. These dissimilarities can cause positional discrepancies that lead to unnecessarily high rates of data transmission during steady flight. This report describes two causes of such positional discrepancy that were encountered and resolved during the conversion of a simulation network from the SIMNET protocol to the DIS. Analysis showed that the methods of resolving these discrepancies are applicable to any dissimilar systems, but they cannot hide all the anomalies caused by a mismatch between systems. Recommendations are made for earth representations in existing simulators that may be used in a DIS network with minimum problems. The recommendations include defining the properties of "good" map projections and a method for eliminating some positional discrepancies between dissimilar networked systems.

14. SUBJECT TERMS
Dead reckoning; DIS; Distributed Interactive Simulation; Flight path distortion; Flight simulation; Legacy systems; Networking; Networks; Network interface unit; NIU; RVA; SIMNET; Threshold testing; WGS-84

15. NUMBER OF PAGES
28

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION ABSTRACT
Unclassified	Unclassified	Unclassified	UL

CONTENTS

List of Figures

ELIMINATING POSITIONAL DISCREPANCIES ENCOUNTERED DURING INTEGRATION OF DISSIMILAR SYSTEMS ON A DISTRIBUTED INTERACTIVE SIMULATION NETWORK

INTRODUCTION

The Aircrew Training Research Division of Armstrong Laboratory (AL/HRA) conducts research and develops technologies and methodologies for training United States Air Force combat aircrews. The technology emphasizes modeling and simulation to develop training systems and support behavioral research studies. During the last several years the engineers at AL/HRA have implemented networked simulation systems to investigate, analyze, and improve aircrew training. The laboratory has supported multiship, joint service, and transatlantic distributed simulation demonstrations and exercises.

The simulation community currently faces the challenge of using the Distributed Interactive Simulation (DIS) protocol to network many long-established simulation systems that were developed independently of each other and of DIS. These systems operate at a variety of update rates, with differing earth representations, and with parameters in different axis systems. However, the systems must integrate smoothly without positional discrepancy.

This report describes two distinct causes of positional discrepancy that were encountered and resolved soon after the conversion of the network to the DIS protocol while also changing the simulation components. Both types of positional discrepancy caused unnecessarily high rates of data transmission during steady flight. The effect was especially apparent during in-flight refueling operations, when the high rate of data transmission led to obvious and frequent small discontinuities in tanker motion.

The earlier system configurations used the Simulator Networking (SIMNET) protocol, enhanced at AL/HRA to support flight simulation requirements. One of the final uses of SIMNET was in the Situation Awareness study. In this study, 68 mission-ready F-15 pilots fought a total of 1,436 engagements in pairs to investigate the components of situation awareness and whether situation awareness can be taught. During each engagement, two F-15 pilots fought against two manned and numerous computer-generated threats. Most of the systems in the network used a relatively similar earth representation, thus avoiding positional discrepancies despite the representation being unrealistic.

The current system configuration, used for the Fighter Fatigue study, implements the DIS protocol to support both local and wide-area network operations. In this Fighter Fatigue study, pairs of combat pilots in networked F-16 fighter simulators first performed a nine-hour transoceanic deployment, refueling frequently on the way. Once deployed, these crews alternated rest periods with a sequence of offensive and defensive combat missions which included air-to-air refueling. The missions were performed at an increasing tempo with decreasing rest time over a period of several days. The threat and tanker models were computer-generated simulations originating at a separate node on the network. In this network configuration, most of the systems used realistic earth shapes, except that the threat and tanker model simulator kept its unrealistic and unsuitable map projection.

The unsuitable map projection, integrated with a system using a more realistic earth shape, caused position discrepancies that led to unnecessarily high rates of data transmission. This problem was solved by the generation of factors applied to the velocity and acceleration components that are used in the Remote Vehicle Approximation (RVA) calculations. A second cause of high data transmission rates during development for the Fighter Fatigue study was error accumulation during the integration of map coordinates in single precision floating point format. The solution was to keep track of the accumulation of error and compensate periodically before it could become significant.

More rigorous analysis performed at the conclusion of the Fighter Fatigue study showed additional small acceleration terms that should have been included in the RVA calculations. The results of this analysis are included herein.

Analysis of the map projection problem shows that although the velocity factors cured the problem of high rates of data transmission, they cannot cure all the anomalies caused by greatly mismatched systems. The analysis led to system requirements, presented herein, for integrating different but realistic earth representations, including "good" map projections. The use of velocity factors is included in these requirements.

SYSTEM DESCRIPTION

This section describes different types of earth representation used in simulation, then presents the system configurations used for the Situation Awareness Study using the SIMNET protocol and the Fighter Fatigue Study using the DIS protocol. Finally, a brief explanation is given of threshold testing of the dead-reckoning calculations.

Earth Representations Used in Simulation

Different simulators may use different forms of earth representation. Some simulators treat the earth as flat, others as curved. Curved surfaces may be either spherical or ellipsoidal. The ellipsoid may or may not have the dimensions of the World Geodetics System 1984 (WGS-84), which is the DIS standard.

In a flat earth representation, or map projection, mean sea level is represented by a plane containing the mutually perpendicular Northing and Easting axes. The Up/Down axis is perpendicular to this plane and represents altitude above or below mean sea level. The algorithm selected to relate Northing and Easting to latitude and longitude defines the map projection.

On a spherical or ellipsoidal earth in this simulation, mean sea level is assumed to be on the reference surface; the difference between the reference surface and real mean sea level, the "geoid," is ignored. Geocentric coordinates describe position in rectangular Cartesian coordinates with the origin at the earth center. Geodetic coordinates describe position in terms of latitude, longitude, and altitude. These two systems are illustrated in Figure 1.

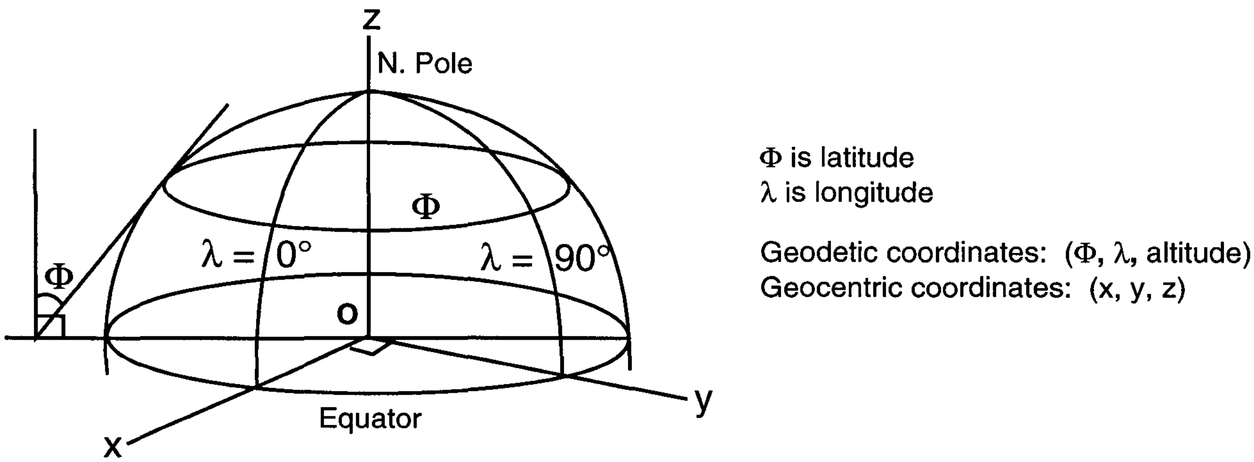
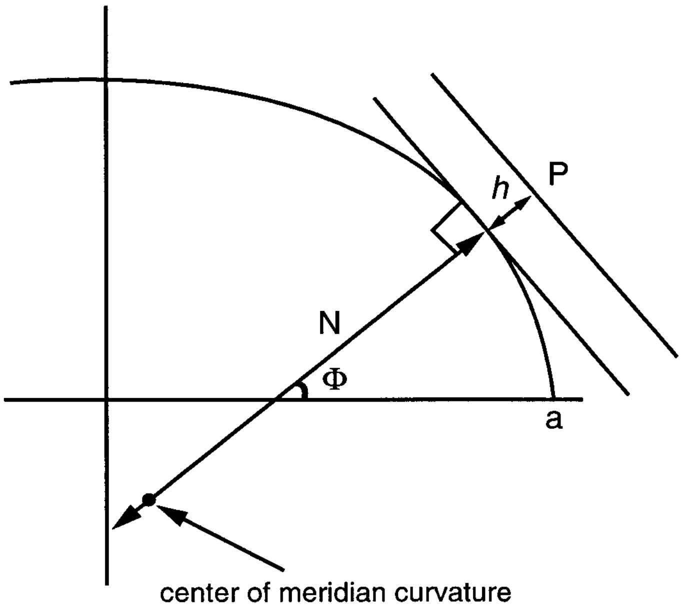


Figure 1
Geocentric and Geodetic Coordinates

Directly or indirectly the earth representation equations define the differential relationship between northerly and easterly linear motion and the corresponding changes in latitude and longitude. The instantaneous local values may be expressed as feet per degree north or east. For an ellipsoidal earth model, the feet to degree relationships are derived from the feet per radian relationships shown in Figure 2.

If the equations of motion in a flight simulation integrate latitude and longitude from northerly and easterly velocity, the values of feet per degree used should be appropriate to the earth model. Conversely, the earth model may be derived from the equations of motion. It sometimes happens that the equations of motion are such that no real shape can be derived. Such a nonsensical result is shown later, in discussion of the F-15 simulation in the Situation Awareness study.

Map projections are at the core of the more significant of the two problems discussed in this report and are addressed in general terms in the following paragraphs.



Earth reference shape is defined as an ellipsoid generated by rotating ellipse about semi-major axis.

a: equatorial radius (ft)
e: eccentricity
Φ: geodetic latitude (radians)
λ: longitude (radians)
s: incremental distance at *h* above surface

$$N = \frac{a}{\sqrt{1 - e^2 \times \sin^2 \phi}}$$

At the point P, *h* above the surface:

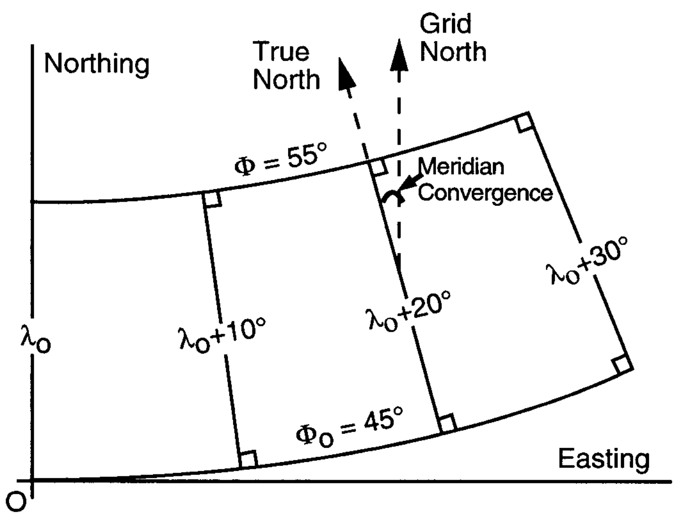
$$\frac{\partial s}{\partial \phi} = h + N \times \left(\frac{1 - e^2}{1 - e^2 \times \sin^2 \phi} \right) \text{ (ft/Radian)}$$

$$\frac{\partial s}{\partial \lambda} = (h + N) \times \cos \phi \text{ (ft/Radian)}$$

Figure 2
Relations at h Above Ellipsoid Surface, Feet Per Radian of Latitude or Longitude

Figure 3 shows a “Good” map projection within which to simulate vehicle dynamics. It also shows meridian convergence, the angle between grid north and true north--true north lying along the projection of a line of longitude. The map projection must be conformal, or a very close approximation to conformal, the closeness being defined by the simulation requirements. Conformal means that, at any given location, longitude projects perpendicular to latitude and the northerly scale equals the easterly scale, and hence scale, at a point, is the same in all directions. A further requirement is that the scale be slow changing with location, and be very close to 1.0 in the gaming area. These requirements force a representation in which shape, range, and bearing are closely preserved over a selected part of the world. As an example, on a Lambert conformal conic, the scale is maintained to within one part in one thousand while latitude is within 2.5° of the origin. To transform between true north-east axes and map grid axes when going into or out of this projection, rotate heading, velocity, and acceleration through the meridian convergence. This is only a minor inconvenience when designed in from the start.

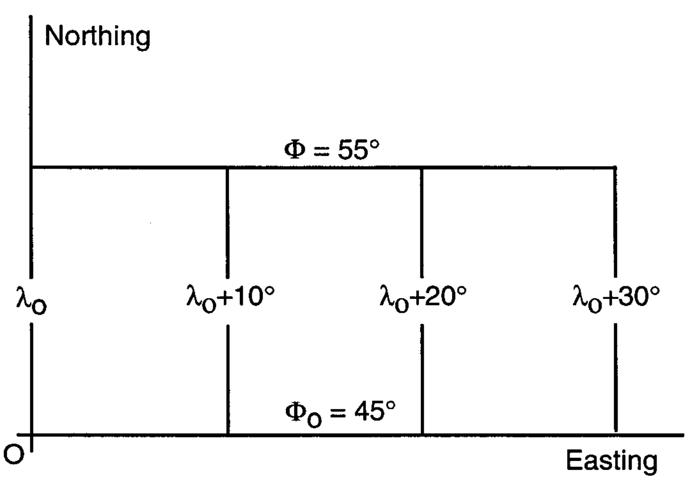
Figure 4 shows a projection that is frequently found in simulation. Serious cartographers do not use it, so it lacks a formal name. To remedy this, we will call it the Popular Not Very Good (PNVG) map projection. People love it because the algorithm is so simple and because latitude and longitude form a rectangular grid with zero meridian convergence. The northerly scale is 1.0 everywhere, while the easterly scale is 1.0 at the latitude of the origin. Unfortunately, there are serious difficulties with the PNVG projection. For instance, the lines of longitude do not converge. Therefore, except near the latitude of the origin, the value of feet per degree of longitude differs significantly from that on the surface of the earth thus the easterly scale is not close to 1.0 everywhere.



(a) Conformal or close to it:
- Longitude perpendicular to latitude
- Scale at point same in all directions

(b) Scale close to 1.0, changes slowly

Figure 3
"Good" Map Projection

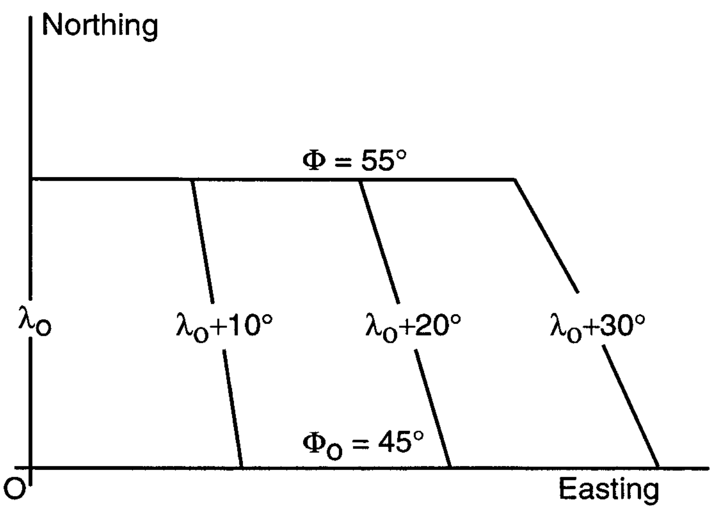


Δ lat = $\Phi - \Phi_O$ (radians)
Δ lon = $\lambda - \lambda_O$ (radians)

Projection of sphere:
Northing = earth radius $*$ Δ lat
Easting = earth radius $*$ Δ lon $*$ $\text{Cos}\Phi_O$

Figure 4
Popular Not Very Good (PNVG) Map Projection

Sometimes in simulation, the PNVG projection is modified by replacing the cosine of the latitude of the origin with the cosine of the latitude of the point being projected, to make the easterly scale 1.0 everywhere and to make the longitudes converge. That creates the Sinusoidal or Mercator Equal Area projection, shown in Figure 5. However, for simulation purposes, this might as well be called the Other Popular Not Very Good (OPNVG) map projection. The OPNVG map projection merely creates a different set of problems because latitude no longer projects perpendicular to longitude; thus north is not perpendicular to east. Also, away from the central meridian, the northerly scale is no longer 1.0.



Δ lat = $\Phi - \Phi_O$ (radians)
Δ lon = $\lambda - \lambda_O$ (radians)

Projection of sphere:
Northing = earth radius * Δ lat
Easting = earth radius * Δ lon * CosΦ

Easterly scale = 1.0
Northerly scale $\neq$ 1.0 away from λ_O
True north not perpendicular to east

Figure 5
Sinusoidal or Mercator Equal Area Projection
Other Popular Not Very Good (OPNVG) Map Projection

Enhanced SIMNET Configuration Used In Situation Awareness Study

Figure 6 shows the SIMNET configuration for the Situation Awareness Study. The components are briefly discussed as follows:

SIMNET Network Interface Units (NIUs). The NIUs and their simulators (hosts) communicated model position to each other in geodetic coordinates, with velocity in north, east, down components. Data transfers across the network and position integration were performed in flat earth coordinates, the NIU transforming position from geodetic to flat earth and back using a map projection. The SIMNET protocol specifies that the Universal Transverse Mercator (UTM) be used for this transformation, but the NIU was an early development and utilized the PNVG projection.

To reduce network traffic, the SIMNET NIU sends the host state vector to the network at infrequent intervals in a vehicle appearance Protocol Data Unit (PDU). The intermittent data received over the network from other nodes are updated regularly by the RVA, or "dead reckoning," algorithm in the NIU for transmission to its host. The RVA is reinitialized to the new state whenever a fresh PDU arrives. The decision when to send a fresh PDU is based upon "threshold testing," a comparison of the expected output from the RVA in other NIUs with the latest output from the host. This is described more fully in a later section.

Automated Threat Engagement Simulator (ATES). The threat generator flew its own models in single precision flat earth coordinates in meters, integrating position from the velocity components. For transmission to the NIU, the position was transformed into geodetic coordinates by inverting the PNVG map projection. Models from the network were positioned into the threat generator's flat earth coordinates via the PNVG map projection. The ATES originally used the sinusoidal map projection, but before the Situation Awareness Study began this was changed to PNVG to be consistent with the other principal components in the network.

F-15 McDonnell Douglas Reconfigurable Cockpits (MDRCs). At first glance, the equations of motion integrating geodetic position from velocity appeared to fly the aircraft over an ellipsoidal earth. However, it was found that the feet per degree relationships for all MDRC systems were calculated during position initialization and were unchanged thereafter. During the Situation Awareness Study, the aircraft were generally initialized at the south end of the gaming area, near the origin of the NIU and the ATES PNVG projection. This approximates flying in the PNVG map projection, since the velocity roughly equals the rate of change of the position projected into the PNVG. No real earth shape can be derived from the equations because the constant size of a degree of longitude implies a cylindrical shape, but on a cylinder all locations are at zero latitude; this is a nonsensical result.

SU-27 Combat Engagement Trainers (CETs). These piloted opposition forces were the only models flying in an earth representation significantly different from the others, the integration of geodetic position corresponding to a spherical earth.

Advanced Visual Technology System (AVTS). The AVTS is a high-end, 10-channel, dual viewpoint, 60-Hz image generator that was the forerunner for Compuscene IV. It uses a spherical earth relation to transform geodetic to geocentric coordinates for scene generation. The differences between this sphere and the PNVG map, within which the MDRC calculated radar vectors to the targets, led to noticeable misalignment between the MDRC Target Designator (TD) box and targets in the AVTS visual display, but it did not affect the study.

Component Combination. The similarity of most of the earth representations used for position integration saved the Situation Awareness Study from many serious problems. The CET SU-27s were an exception, but since they were on the opposition force, there was no requirement for close formation or close visual observation, so the study was not affected. However, the aerial refueling requirements of the Fighter Fatigue Study and a change to dissimilar systems in the DIS network led to the two problems discussed herein.

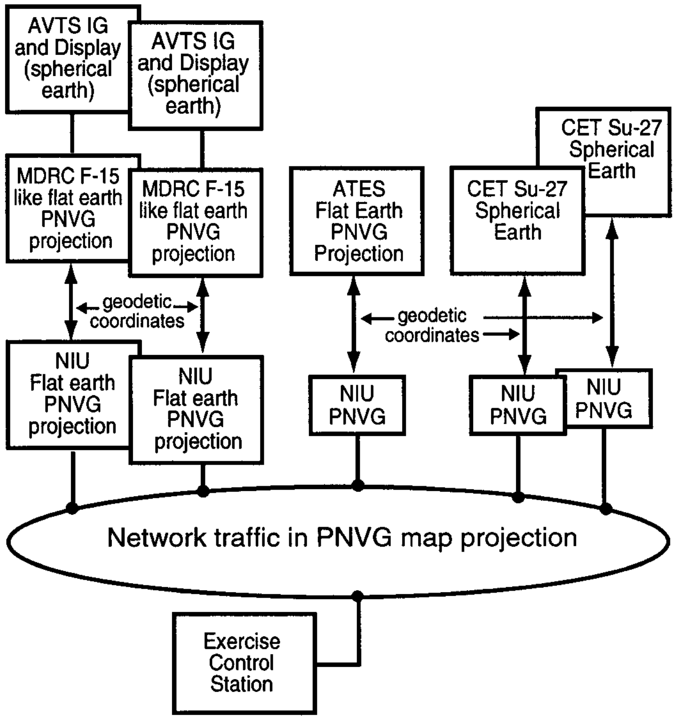


Figure 6
Situation Awareness Study Configuration, SIMNET Protocol

DIS Configuration Used In Fighter Fatigue Study

Figure 7 shows the configuration for the Fighter Fatigue Study. The components are briefly described as follows:

DIS NIUs. The NIUs still communicate with their hosts in geodetic coordinates, with velocity in north, east, and down. However, the data transfer over the network is no longer in flat earth, but has been changed to geocentric coordinates, with the transformation from geodetic and back conforming to the DIS standard of the WGS-84 ellipsoid. The integration of position from velocity also corresponds to the WGS-84. An improvement relative to the Situation Awareness study was the incorporation of linear acceleration and rotational rates into the dead reckoning algorithms.

F-16 Weapon System Trainers (WSTs). The equations integrating geodetic position from north and east velocity imply an ellipsoidal earth surface close to that of the WGS-84.

Therefore, there were no significant earth representation problems when integrating with the WGS-84 NIU.

AVTS. The image generator spherical earth is unchanged. The difference from an ellipsoid caused no observable problems when integrated with the WSTs, although analysis suggests alignment errors of up to 2 milliradians occur at the mid latitudes.

ATES. The ATES earth representation is unchanged. It still uses the PNVG map projection. The inconsistency between this representation and the more realistic representations introduced elsewhere into the DIS network led to the principal problem discussed herein. In addition to generating threats, this simulator also generated the KC-135 tanker model for the Fighter Fatigue Study.

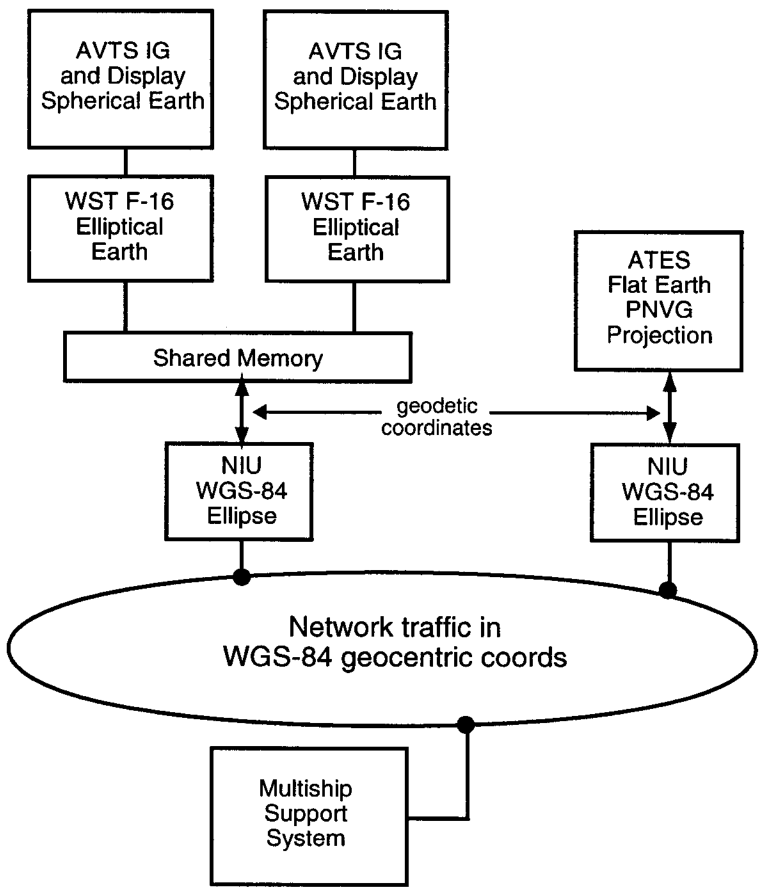


Figure 7
Fighter Fatigue Study Configuration, DIS Protocol

NIU Threshold Testing

Figure 8 shows the NIU threshold testing described here to help explain the positional discrepancies.

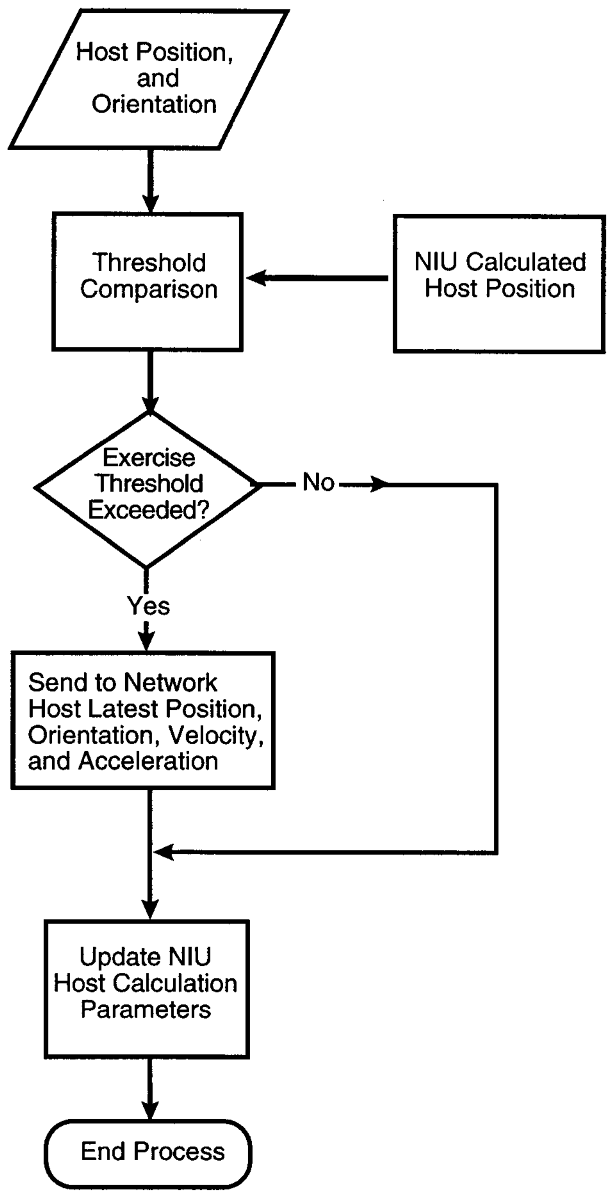


Figure 8
NIU Host Entity Threshold Testing of Dead Reckoning Calculation

To determine when to send an updated DIS entity state (or SIMNET vehicle appearance) PDU, the sending NIU performs a trial dead reckoning calculation, mimicking the RVA and continuously predicting ahead in time to check for discrepancies against the latest position and attitude from the host. When any discrepancy exceeds a specified threshold, the latest host data are put onto the network, and the integration for threshold testing is restarted from this new condition. For most models, the position threshold value is 1.0 m, but for the ATES tanker, this was reduced to 0.5 m. The maximum allowable interval between entity state PDUs is 5 s, "the heartbeat," no matter how small the discrepancies.

Position discrepancies in steady flight should be extremely small, even after a 5 s interval. However, inconsistencies between the ATES earth representation and that of its NIU in the Fighter Fatigue Study led to a faster-than-reasonable buildup of discrepancies and more frequent PDU transmissions. The discovery and elimination of these problems is described in the following section.

PROBLEM DISCOVERY AND CURE

This section describes the discovery and correction of two positional discrepancy problems encountered during system development for the Fighter Fatigue Study. The first problem resulted from differences in earth geometry representation, and the second was caused by differences in computational precision. Both caused excessive rates of data transmission around the network.

Problem #1. Effect of Earth Representation Differences

Figure 9 shows the ATES tanker racetrack pattern for the deployed refueling task, with the more southerly leg positioned 37 km north of the PNVG map origin. The tanker is flying at a constant 425 kt true airspeed (KTAS). During the steady east or west legs, the tanker was breaking NIU thresholds frequently, causing the NIU to send PDUs more often than expected. The frequency was greater on the more northerly of the two legs. For demonstration purposes, legs were run at locations progressively farther north of the origin, and the PDU rate during east-west flight increased with northerly displacement.

This problem resulted from the NIU change to use the WGS-84 ellipsoid. This representation, though more realistic than previously, was not consistent with the ATES PNVG map projection in which the easterly scale diverges rapidly from 1.0 as northerly displacement from the origin is increased. The rate of buildup of discrepancy is proportional to the ratio of the value of feet per degree of longitude used in the ATES PNVG map projection and the corresponding value for the WGS-84 in the NIU. This ratio is approximately equal to the cosine of latitude divided by the cosine of the latitude of the map origin. It was shown that the variation in measured PDU rate was closely explained in terms of this ratio, the aircraft speed, and the size of the threshold.

There was no time for a proper rework, such as changing to a good map projection in the ATES, rebuilding the database, and applying all the proper rotations for meridian convergence. However, a quick fix for the high PDU rate problem was implemented, making use of the ratio of values of feet per degree just mentioned.

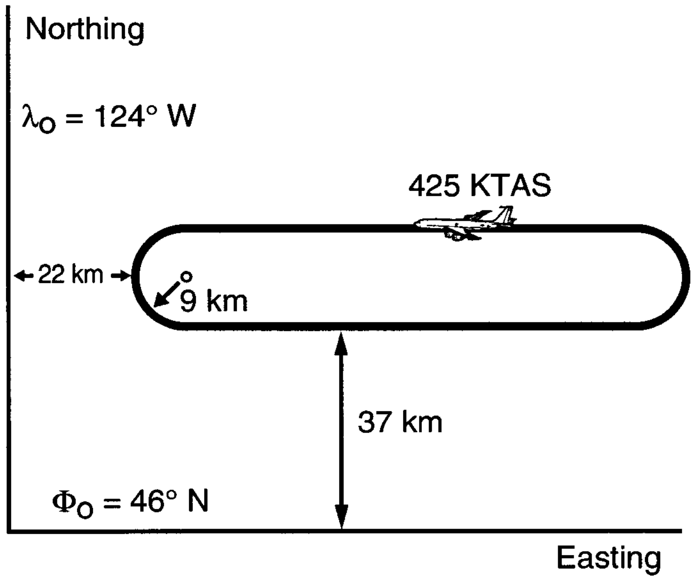


Figure 9
Tanker Racetrack Pattern in ATES PNVG Map Projection.
Location During Early System Development for DIS.

Figure 10 shows this correction, which allows the ATES to apply the appropriate feet per degree ratio as a velocity factor to each of the velocity and acceleration components sent from the ATES to its NIU. The factored velocity predicts a rate of change of geodetic position in the WGS-84 that corresponds to the position changes coming from the ATES. Since the NIU was already computing the WGS-84 feet per degree values, it was simpler in this configuration for the ATES to ship the PNVG constant feet per degree values to the NIU and have the NIU calculate the ratios and factor the velocity and acceleration components. The factored components were used in the threshold testing position integration and also sent over the network in the entity state PDUs. This solved the problem, kept the discrepancies small, expanded the PDU interval back to 5 s over the straight portions of the racetrack pattern, and allowed us to run the Fighter Fatigue Study.

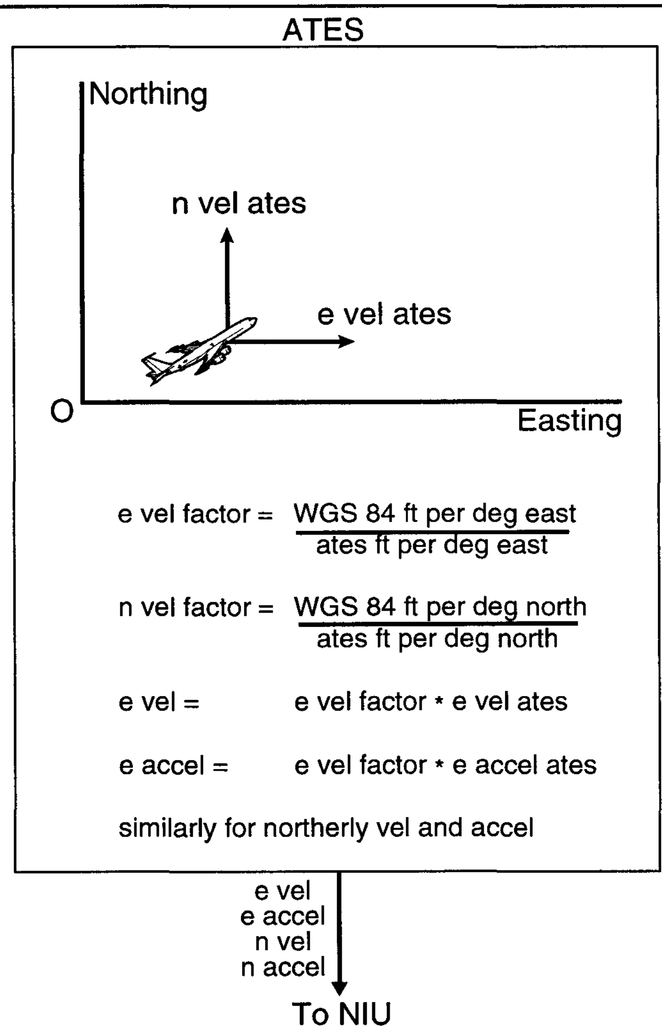


Figure 10
Quick Fix for High PDU Rate Due to PNVG Map Projection

Problem # 2. Position Integration Precision

Figure 11 shows the ATES tanker track for the transoceanic deployment refueling task in the Fighter Fatigue Study.

For each transoceanic refueling scenario, the ATES makes a fresh PNVG map projection with the origin near the start location of the task. After the initial turn, the tanker heads steadily east, getting farther and farther from the origin. During development of this task, the PDU rate was found to increase with range from the ATES local scenario map origin despite the application of the velocity factors. This range from the local origin was sometimes as large as 300 km, especially during system development.

This problem resulted from the accumulation of errors in the ATES integration of position coordinates in single precision floating point format when compared to the double precision WGS-84 calculations in the NIU threshold testing. In IEEE single precision format, at coordinate values between 131 and 262 km, the least significant bit (LSB) represents 15.6 mm with the error doubling for each doubling in range. When the system was first delivered, this resolution was thought to be acceptable. However, although an error of 15.6 mm may be acceptable one time, accumulation at the ATES update frequency of 20 Hz breaks the tanker half-meter threshold every 1.8 s. In practice, the error accumulation rate fluctuates with small changes in the desired position increment, hence, with small changes in speed. The position discrepancy is along the flight path for the track shown in Figure 10. However, if the tanker were to turn northeast when a long way east of the origin, the discrepancy buildup would have a component across the flight path.

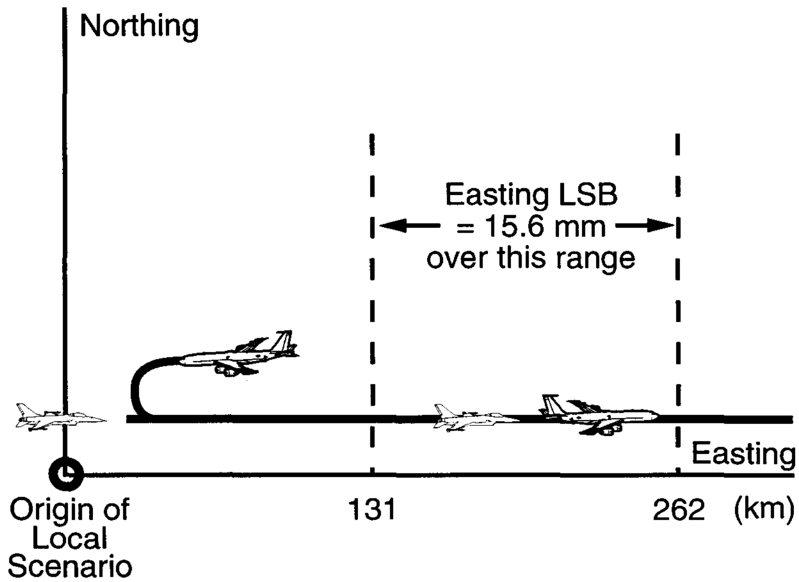


Figure 11
ATES Single Precision Coordinate Resolution on Transoceanic Refueling Task

It was impractical to change the ATES position coordinates to double precision as too many changes would need to be made in too many places in too little time. Instead, to solve this problem, the accumulation of error was tracked and compensation periodically applied before it could become significant.

Figure 12 shows the rather cumbersome algorithm developed overnight to compensate for the error accumulation. It is shown applied to the x (or Easting) position coordinate. It was also applied to the y and z coordinates. This algorithm solved the problem, and the interval between

PDUs went back to the 5 s maximum with very small position discrepancies. Figure 13 shows a simpler algorithm we thought of later!

```
float x, x_vel, x_accel, x_accel_dot; /* inputs */
float dt;                  /* integration time interval */
double dx, x_prev, x_loss_test
static double x_loss; /* value still owed to x after previous integration. */

  /* Calculate test value between magnitude of second and third least significant bits of x variable.
Remember the mantissa in IEEE float is implied 1, with 23 bits. */

   x_loss_test = fabs(x) * .23E-6;
   /* pow(2,-22) = .238E-6  */

  /* Perform x integration, tracking error accumulation and compensating when large enough. */

   x_prev = x;
  /* Calculate increment in x over time, dt, due to velocity and its change.  */
   dx = ((x_accel_dot * dt/3 + x_accel) * dt/2 + x_vel) * dt;

   if(fabs(x_loss) > x_loss_test)
      /* Try to increment x by ( x_loss + dx). */
      x = x + x_loss + dx;
   else
      x = x + dx;

   /* Update x_loss. */
   x_loss = x_loss + dx - ((double)x - x_prev);
```

Figure 12
Algorithm Used to Prevent Error Accumulation During Single Precision Integration

VELOCITY FACTORS DO NOT PREVENT ALL ANOMALIES

The velocity factors discussed in the previous section can be applied to the interface between any host and its NIU to prevent most of the positional discrepancies in the RVA caused by differences in earth representation. The following points are presented:

- With an acceptable earth representation the velocity factors will be close to 1.0, but may still differ enough from 1.0 for compensation to be needed:
- At 1,000 ft/s, one part in 1,000 error will build discrepancy at 1 ft/s.
- The integration of a spherical earth with a WGS-84 ellipsoid may cause discrepancies of one or two parts in 1,000 at mid latitudes.
- On a "good" conformal map projection of the WGS-84 ellipsoid, the velocity factor is about:

vel_factor approx = (alt + earth radius)/(earth radius * local map scale).

```
float x, x_vel, x_accel, x_accel_dot;          /* inputs */
float dt;        /* integration time interval */
double dx, x_prev;
static double x_loss;          /* value still owed to x after previous integration. */

   x_prev = x;
   /* Calculate increment in x over time, dt, due to velocity and its change. */
   dx = ((x_accel_dot * dt/3 + x_accel) * dt/2 + x_vel) * dt;

   /* Try to increment x by (x_loss + dx). */
   x = x + (x_loss + dx);

   /* Value still owed to x is what we tried to add, less what actually got in. */
   x_loss = x_loss + dx - ((double)x - x_prev);
```

Figure 13
Improved Algorithm to Prevent Error Accumulation During Single Precision Integration

Although it prevents RVA positional discrepancies, the application of velocity factors cannot hide some anomalies caused by seriously inconsistent earth representation. For instance, consider the fairly extreme case of an ATES model flying at a location where the easterly velocity factor is 0.8 and the northerly factor is 1.0. On the PNVG map with an origin latitude of 60°, such a situation would occur at 66.4° latitude, whereas on a "good" map projection, such as a Lambert conformal conic, the corresponding velocity factor would be about 0.993 in all directions. Two examples of the resulting anomalies are presented in the following paragraphs.

The first example, Figure 14, shows the model flying a circular path in the map at a constant speed of 400 kt. When successive positions are projected into the network, the position rates of change correspond to speed increasing from 320 to 400 kt as the model turns from east to north, followed by a decrease back to 320 kt as it turns onto west. The circular path in the map is squashed from east to west in the network, becoming elliptical. On the north-south sectors, with the speed in the network unaltered relative to that in the map, the centripetal acceleration is reduced by 20%; hence, the rate of change of track is reduced by 20% relative to that in the map, but the yaw rate is unaltered. A constant and correct bank angle of 28° in the map is 5° too large for the centripetal acceleration in the network on the north-south sectors. On the east-west sectors, the bank angle and centripetal acceleration are in agreement, but in this case, the rate of change of track has been accelerated and is now faster than the constant yaw rate.

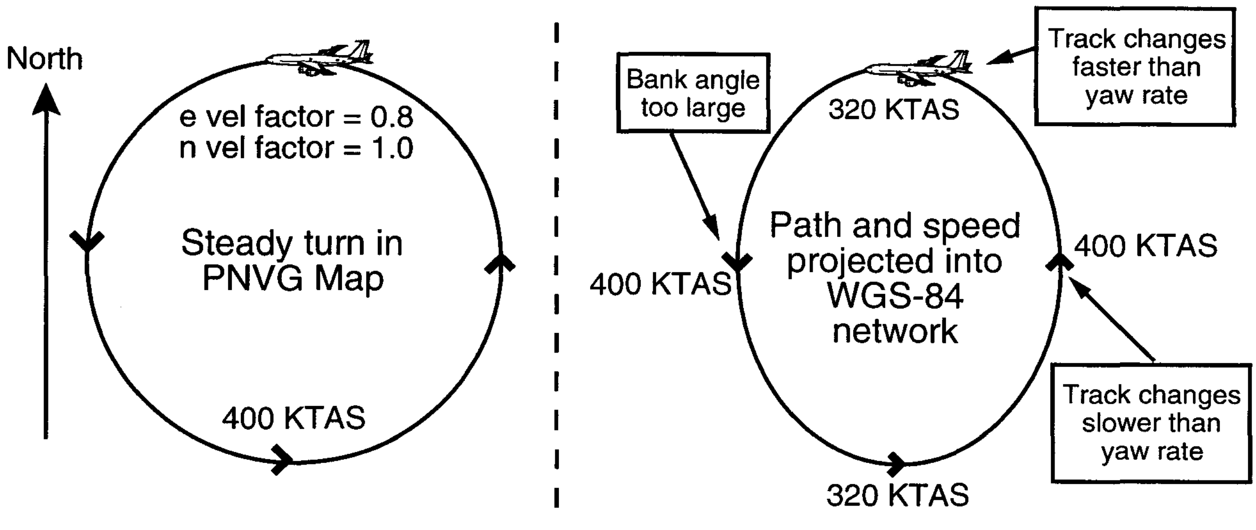


Figure 14
Distorting Effect of PNVG Map Projection on Velocity and Flight Path Sent to Network

The second example, Figure 15, shows the model in the map on a constant heading of 45° with a speed of 400 kt. The model track projected into the network is 38.7° with a speed of 362 kt, but heading is unaltered at 45°. From a following WST, the model would be seen to be slow and drifting to the left by 6.3°. Analysis shows that some drift is caused on all headings except due north, south, east, and west.

By extending the argument in the preceding examples, discrepancies can be shown in the range and bearing to targets.

Note that the anomalies are caused by the mismatch in earth representation, not by the velocity factors. The velocity factors match the projected velocity to the rate of change of projected position, serve as a measure of the mismatch, and prevent some types of positional discrepancy. These anomalies and the misalignment of the MDRC TD box, all caused by integrating the PNVG map projection with more realistic earth models, are summarized below:

- F-15 MDRC target designator box misalignment
- Wrong velocity sent over network
- "Constant" speed changes with heading
- Circular path in map becomes elliptical in network
- Bank angle, yaw rate, and track rate inconsistent
- Models will drift on most headings
- Incorrect relative bearings
- Incorrect ranges

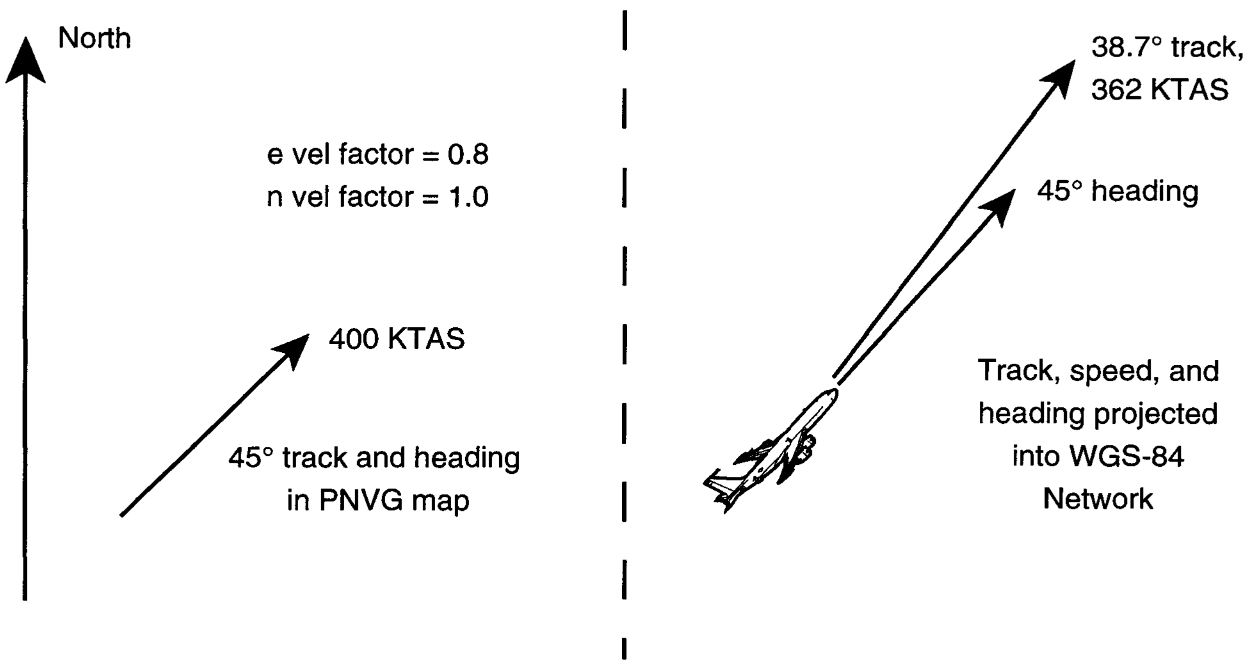


Figure 15
Drift and Speed Error in the Network Caused by PNVG Map Projection

Despite the gross anomalies caused by integration between the poor map projection and the WGS-84, use of the velocity factors prevents high PDU rates caused by positional discrepancies. The reciprocals of the velocity factors should be applied at the host to the incoming velocity and acceleration components from external systems to ensure correct prediction of target flight path and aiming of unguided weapons within the host's earth representation.

TRANSFORMATION OF ACCELERATION TERMS BETWEEN MAPS AND WGS-84

The application of velocity factors to velocity and acceleration was a quick fix that prevented large position discontinuities along the tanker track during the Fighter Fatigue Study.

The acceleration components in the transformation from the ATES PNVG map to the WGS-84 can more rigorously be derived by differentiating the velocity transformation equations with respect to time. For simplicity, the acceleration terms have been derived by differentiating the equations to transform velocity from the PNVG map to a sphere, leading to the expressions for e_accel and n_accel shown in Figure 16. Figure 16 also shows the contribution to upwards acceleration over the ellipse that accounts for the effect of downward surface curvature compared with the flatness of the map projection. This may be considered a V^2/R term.

$$e\_accel = e\_vel\_factor \times e\_accel\_ates + \frac{e\_vel \times \dot{h}}{earth\_radius + h} - \frac{e\_vel \times n\_vel \times \tan lat}{earth\_radius + h}$$

$$n\_accel = n\_vel\_factor \times n\_accel\_ates + \frac{n\_vel \times \dot{h}}{earth\_radius + h}$$

$$\ddot{h} = \ddot{h}\_ates - \frac{n\_vel^2 + e\_vel^2}{earth\_radius + h}$$

Where h is altitude AMSL,
e_accel, n_accel, n_vel, e_vel, $\ddot{h}$ are values projected into WGS-84,
$\dot{h}$ is the same in both systems.

Figure 16
Projection of Acceleration Terms From PNVG Map into WGS-84

The components involving the velocity factors are identical to those shown in Figure 10 and used in the Fighter Fatigue Study.

The components involving rate of climb apply to flight over any map projection. A combination of 1,000 ft/s upwards with 1,000 ft/s horizontal produces about .05 ft/s^2 of horizontal acceleration when projected into WGS-84. This fairly extreme case causes about 7.5 in. of displacement at the 5-s heartbeat. In practice, such extreme climbing flight is unlikely to be steady, so thresholds will be broken due to other effects long before the heartbeat. For that reason, these terms involving rate of climb may be ignored.

The V^2/R term in $\ddot{h}$ applies to flight over any map projection. At 1,000 ft/s steady level flight, the term causes about 7.5 in. of vertical displacement at the 5-s heartbeat, and therefore should be included.

The $(e\_vel \times n\_vel)$ component of e_accel results from the lack of longitude convergence in the PNVG which causes the easterly map scale to change rapidly with northerly distance from the origin. At 1,000 ft/s on a NE heading at 63° latitude, this component causes about 7.5 in. of displacement at the 5-s heartbeat. For "good" map projections, analysis shows that there should be $(e\_vel \times n\_vel)$ terms in one or both directions, resulting from the rate of change of map scale with displacement. However, on "good" map projections, these terms will be negligible due to the extremely low rates of change of map scale.

The contribution of these acceleration terms to the earlier described distortion of velocity and flight path shown in Figures 14 and 15 have been analyzed. The analysis shows that it is the $(e\_vel \times n\_vel)$ term in e_accel that corresponds to the long-term history of speed and track rates of change as the model flies on a 45° heading. However, this term is not significant in the distortion of the circle to an ellipse and the corresponding speed changes; this can be deduced because nothing changes the contribution as a function of the tightness of the turn. It is the combined effect of the velocity ratios on acceleration and velocity that transforms purely radial acceleration in the PNVG map into acceleration in WGS-84 that has a trackwise as well as a radial component and which corresponds to the rate of change of speed and distortion of the circle projected into WGS-84.

In summary, when projecting acceleration from any map projection into WGS-84, apply the velocity factors to the horizontal accelerations and subtract the V^2/R term from $\ddot{h}$. When projecting from the PNVG map projection into WGS-84, also subtract the $(e\_vel \times n\_vel)$ component in e_accel. When projecting acceleration from WGS-84 into the map, use the reciprocals of the velocity factors and change the signs of the other components.

LESSONS LEARNED

This report shows some of the problems that arise when integrating dissimilar systems. Depending on the simulation requirements, a bad earth representation can be fatal. The problems encountered while developing the DIS network at the Armstrong Laboratory emphasized the need for appropriate initial design and led to the earth representation requirements presented in the following section.

Dissimilar Systems

The development of DIS networking cannot be put on hold while all the systems in the world are redesigned to fly in a WGS-84 ellipsoid. We frequently must use what is available. However, in general, we cannot accept the large anomalies caused by seriously inappropriate earth models.

Dissimilar earth representations are acceptable for most simulation requirements, provided the inconsistencies are small. The velocity factors and extra acceleration terms compensate the prediction of rates of change of position and velocity for differences in earth shape, variations in map scale, and the lack of altitude effects over a map. Application of these terms and attention to computation precision will prevent position discrepancies of the type discussed in this report. As is well known, geocentric or geodetic coordinates must be represented as double precision floating point numbers, or at least as 32-bit scaled integers, whereas for maps of small extent, coordinates may be represented as single precision floating point values. In all cases, we must ensure that integration errors do not accumulate. The requirements for acceptable earth representation in simulators on most DIS networks are summarized below:

I. Where practical, use the WGS-84 ellipsoid.

II. Flight in sphere or non-WGS-84 ellipsoid permissible.

(a) Apply velocity factors to velocity and acceleration going from host to NIU.
(b) Apply reciprocal of velocity factors to velocity and acceleration coming from NIU to host.

III. A flat earth representation is permissible.

(a) Use "good" map projection:
 Conformal or close to it:
  North perpendicular to east.
  Scale at point same in all directions.
 Scale close to 1.0 and changes slowly.
(b) Account for effect of meridian convergence on velocity, acceleration, and heading.
(c) Dimensions of map limited by need for scale close to 1.0.
(d) Apply velocity factors as above.
(e) Subtract the V^2/R term from upwards acceleration when projecting into WGS-84.
(f) Add the V^2/R term to upwards acceleration when projecting from WGS-84 into the map.
(g) If using the PNVG map, apply the $(e\_vel \times n\_vel)$ term to e_accel.

IV. Ensure adequate computation precision.

(a) Resolution of individual coordinates.
(b) Prevent error accumulation over time.

Do It Right From The Start

The map projection and other earth representation problems are simple to analyze, once you realize there is a problem. During the design phase, incorporate at the system level the analysis of an engineer who understands these problems and can ensure proper earth representation using the requirements presented here as a starting point.

With inconsistent systems, it is especially hard to predict every problem and determine its significance. When practical, design or acquire systems in which earth representation is consistent with a common standard; life is simpler for the honest man.